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Unsurprising Aspects of Heavy-Ion–Induced Two-Nucleon Transfer Reactions*

K. G. Nair, C. W. Towsley, R. Hanus, M. Hamm, and K. Nagatani
Cyclotron Institute, Texas A&M University, College Station, Texas 77843
(Received 10 July 1975)

An apparent puzzle concerning the suppression of heavy-ion–induced *nn* and *pp* transfers compared to *np* transfer in light nuclei can be explained to a great extent by invoking simple arguments based on the binding energies of the transferred pairs to the two cores. The manifestation of this effect is in the tail regions of the appropriate bound-state wave functions where transfer is well known to occur. These arguments may be extended to include multinucleon transfers where the consequences of this effect could be even more drastic.

Recently, Anyas-Weiss *et al.*[1] have presented data concerning two-nucleon transfer reactions on light nuclei induced by high-energy (≈ 10 MeV/nucleon) heavy ions. It was observed in these studies that the *nn* and *pp* transfer reactions had differential cross sections of the order of 20 μb/sr whereas the *np* transfer differential cross sections were typically 1 mb/sr. They have generalized this result by concluding that the cross sections for $T=0$ transfer are much larger than those for $T=1$ transfer and that for *np* transfer the $T=1$ part may be neglected. While it may be useful to have such empirical rules, it is important to investigate other causes for such differences in cross sections.

In the present study, we report experimental and theoretical results on ^{12}C(^{14}N, ^{12}C)^{14}N, ^{12}C(^{14}N, ^{12}N)^{14}C, and ^{12}C(^{14}N, ^{12}B)^{14}O at 155 MeV as well as some theoretical calculations on three-nucleon transfer data.

A 200-μg/cm^2-thick natural carbon target was bombarded by 155-MeV ^{14}N ions from the Texas A & M cyclotron. Energy spectra obtained simultaneously for the ^{12}C, ^{12}B, and ^{12}N exit channels at $\theta_{lab} = 5.5°$ using standard particle identification techniques[2] are shown in Fig. 1. The present spectrum for the reaction ^{12}C(^{14}N, ^{12}C)^{14}N is similar in its general features to the one taken at 118 MeV by the Oxford University group.[1] However, because of the improved energy resolution of our spectrum (~ 350 keV), additional information can be obtained from our data. Results for comparison are also available from studies on the reaction ^{12}C(α, d)^{14}N.[3] We note that the ^{12}C(^{14}N, ^{12}C)^{14}N channel can in principle include backward elastic and inelastic scattering. However, the selective population of final states (Fig. 1) and the strong forward peaking of their angular distributions (Fig. 2) demonstrate that the reaction is a direct transfer process.

In Fig. 1, the spectra of the (^{14}N, ^{12}B) and (^{14}N, ^{12}N) reactions are inserted for comparison. In the ^{12}N spectrum scattered background counts were recorded due to Landau fluctuations from the very large counting rates in the ^{14}N and ^{13}N channels although the particle identification system was very carefully set. Thus the ground states of ^{14}C and ^{14}O could hardly be seen above the background. Nevertheless, several transitions to the known states in ^{14}O and ^{14}C were ob-

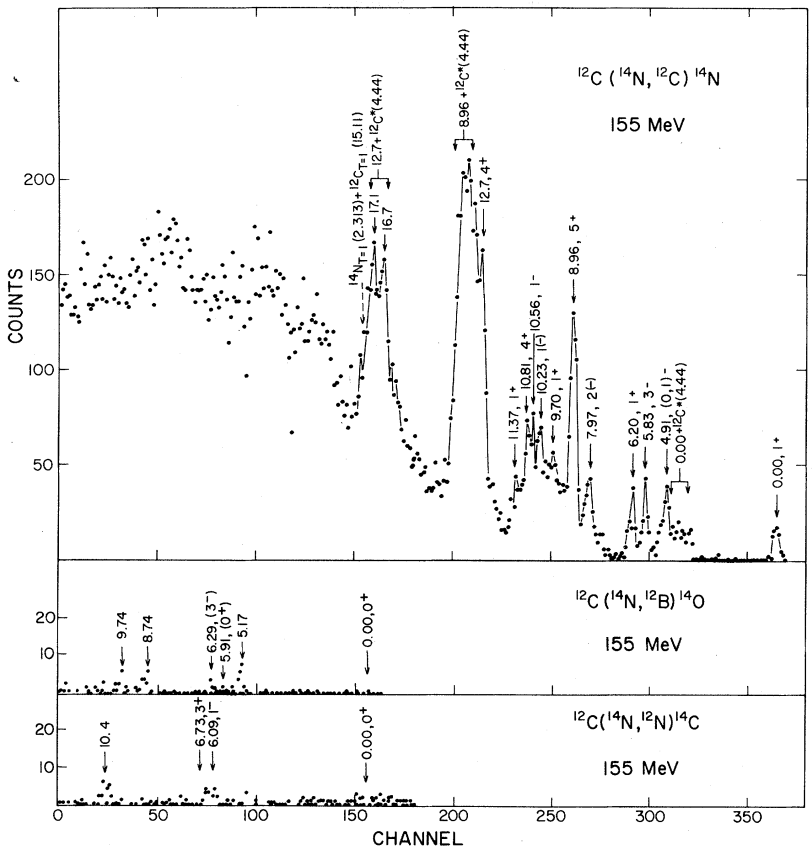

FIG. 1. Energy spectra of the (^{14}N, ^{12}C), (^{14}N, ^{12}B), and (^{14}N, ^{12}N) reactions on ^{12}C at 5.5°. The prominent peaks are identified with the known states in the appropriate residual nuclei. Possible ejectile excitations are also indicated in the top spectrum.

served as indicated in the figure.

A casual inspection of the three spectra in Fig. 1 is enough proof that the *nn* and *pp* transfer cross sections in general are much suppressed compared to that of *np* transfer. However, the crucial point is this: There is no logical basis for making such a comparison and to expect similar cross sections except when the exit channels are comprised of isobaric multiplets. The similarity of transfer cross sections to analog channels in one-[2] and three-nucleon[4] transfer reactions in this mass and energy region has been well established by experimental observation. Thus in the present case comparisons should be made among the three analog-channel reactions corresponding to the exit-channel configurations

$$[^{12}\mathrm{C}(15.11, 1^+, T=1) + {}^{14}\mathrm{N}(2.313, 0^+, T=1)],$$

$$[^{12}\mathrm{B}(\mathrm{g.s.}, 1^+, T=1) + {}^{14}\mathrm{O}(\mathrm{g.s.}, 0^+, T=1)],$$

and

$$[^{12}\mathrm{N}(\mathrm{g.s.}, 1^+, T=1) + {}^{14}\mathrm{C}(\mathrm{g.s.}, 0^+, T=1)].$$

In the present case, the first configuration is situated at a very high level-density region as indicated by the dotted arrow in Fig. 1 and is not clearly observable among the many $T=0$ states populated in this region.

Now we would like to address ourselves to the following question: Why are the cross sections for these $T=1$ pair channels much smaller than the $T=0$ pair channel? Assuming a simple cluster transfer mechanism, it appears that the major differences among these cases are related to the large differences in binding energies of the clusters to the projectile-ejectile system (in the target-residual system they are more comparable) as is shown in Table I. Consequently not only is the matching of the distorted waves affected but also the magnitudes of the appropriate

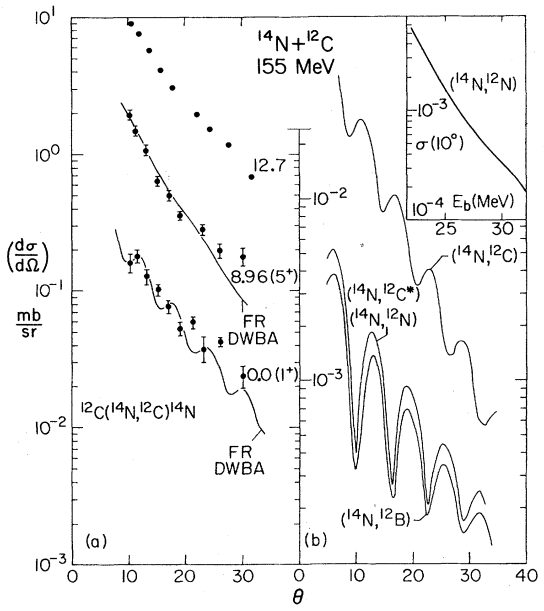

FIG. 2. (a) Experimental and finite-range DWBA theoretical angular distributions for transitions to the ground state and 8.96-MeV states in ^{14}N. Spectroscopic factors are assumed to be unity for the calculation. The experimental angular distribution for the group at approximately 13 MeV excitation is also shown. (b) Calculated differential cross sections for the three $T=1$ analog-channel transfers and for the $T=0$ ground state transfer. The (^{14}N, ^{12}C*) and (^{14}N, ^{12}N) results are too close to be separately shown in the figure. The near-exponential dependence of the cross section on the binding energy of the cluster is illustrated for a typical case in the inset.

bound-state wave functions in the narrow localized region where transfer takes place.

In order to justify the above argument, we have carried out distorted-wave Born-approximation (DWBA) calculations for these reactions. In Fig. 2(a), experimental (^{14}N, ^{12}C) angular distributions for transfer to the ground state and 8.96-MeV state of ^{14}N are compared with the theoretical finite-range (without recoil) DWBA calculations.

Figure 2(b) shows the differential cross sections calculated for the three $T=1$ analog channel transfers and for the $T=0$ ground state transfer using an adapted version[2] of the exact-finite-range DWBA code SATURN-MARS.[5] The appropriate product spectroscopic factors have been included (values taken from Cohen and Kurath[6]). Of course we do not expect the absolute cross sections to be taken too seriously on account of our neglect of the correlation of the two nucleons transferred. However, the relative cross sections emphasize the dynamics of the reactions which have been done correctly in the calculations and are in good agreement with the experimental estimate which gives an upper limit of about 0.02 for the ratio of *nn* or *pp* transfer to the *np* transfer cross section for the appropriate ground state. It is clear from these results as well as from the last column in Table I that the suppression of the (^{14}N, ^{12}C*), (^{14}N, ^{12}B), and (^{14}N, ^{12}N) cross sections is a direct consequence of the increased binding energies of the cluster in the projectile-ejectile system. Figure 2(b) further illustrates this point where the near-exponential variation of the calculated cross section of (^{14}N, ^{12}N), for example, as a function of the cluster binding energy in the projectile-ejectile system is also plotted.

As an extension of this line of argument, we have done additional cluster-transfer calculations on three-nucleon transfers on ^{28}Si induced by 86-MeV ^{11}B ions. This example was chosen since related experimental work[7] is available in literature. The calculated differential cross section (with unit spectroscopic factors) at the measured angle of 11° is 552 nb/sr compared to the experimental value[7] of about 80 nb/sr. In spite of the crude calculation, this is not an unreasonable result and since maximum strengths for the config-

TABLE I. Binding energies and calculated cross sections for two-nucleon transfer.

Reaction $A(a,b)B$	Binding energies (MeV) (A,B)	(a,b)	Q (MeV)	$(d\sigma/d\Omega)$, $\theta_{c.m.}=10°$[a] (mb/sr)
^{12}C(^{14}N, ^{12}C(g.s.))^{14}N(g.s.)	12.49	12.49	0.0	2.47×10^{-2}
^{12}C(^{14}N, ^{12}C(15.1))^{14}N(2.3)	10.48	27.61	−17.13	2.74×10^{-4}
^{12}C(^{14}N, ^{12}B(g.s.))^{14}O(g.s.)	6.57	25.08	−18.51	2.25×10^{-4}
^{12}C(^{14}N, ^{12}N(g.s.))^{14}C(g.s.)	13.12	30.64	−17.52	2.43×10^{-4}

[a]Here the product spectroscopic factor S_1S_2 has been assumed to be unity for all cases.

urations ^{31}Si(g.s.) = ^{28}Si(g.s.) + *nnn* and ^{11}B(g.s.) = ^{8}B(g.s.) + *nnn* are unlikely, theoretical results will be in better agreement with experimental data once the correct values of $S_1 S_2$ are included. The present calculation also verifies the statement of the authors of Ref. 7 that the low cross section for *nnn* transfer follows the trend of high-energy heavy-ion reactions of favoring the transfer of bound clusters. It is worth pointing out in this connection that because of the smaller binding energy of the assumed *nnp* cluster (19.7 MeV) compared to that of the *nnn* cluster (38.5 MeV) in the projectile, the (^{11}B, ^{8}Be) reaction on the same target gives a calculated differential cross section about 12 times larger (6.35 μb/sr) compared to that of the (^{11}B, ^{8}B) reaction (0.55 μb/sr). In planning multinucleon transfer experiments, dynamic effects such as this might be of considerable value to the experimenter.

In conclusion, we have shown that the explanations for the suppression or enhancement of heavy-ion-induced multinucleon-transfer reactions in terms of empirical T-selection rules only may be clouded by dynamic effects such as those caused by binding energies of the transferred clusters to the cores.

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Single-Collision Production of Quasimolecular X Rays in Heavy-Ion Encounters

F. Bell, H.-D. Betz, H. Panke, E. Spindler, and W. Stehling
Sektion Physik, Universität München, 8046 Garching, Germany

and

M. Kleber
Technische Universität München, 8046 Garching, Germany

(Received 19 May 1975)

Remarkably large quasimolecular (molecular orbital) K-shell x-ray yields are found in 48-MeV S→Ne encounters, unequivocally indicating that production of molecular-orbital x-rays can occur as a result of single-collision mechanisms. Gaseous and solid targets are found to give similar spectral shapes of the emitted continuum radiation.

In heavy-ion–atom collisions certain molecular states can be transiently formed. If there is a vacancy in the quasimolecular system electronic transitions between these states may lead to emission of quasimolecular [molecular orbital (MO)] x-ray continua.

Originally, a double-collision mechanism has been postulated[1]: In a first collision an inner-shell vacancy is somehow produced in the projectile ion and is then carried into a second collision where its decay may lead to the observed MO x-ray transition. The exclusiveness of this mechanism appeared to be backed up by recent experiments in gas targets; for example, Saris *et al.*[2] concluded that L-shell MO x rays from 300-keV Ar-Ar collisions are absent when the incident Ar ions have no initial L vacancy. Assumption of the double-collision mechanism implies that the initially produced vacancy must survive the time which elapses between the two collisions. However, since total lifetimes of vacancies and shell radii decrease strongly with increasing nuclear charge, Z, of ions, MO x-ray production would also decrease for heavier collision systems and would become difficult to observe for the heaviest projectile ions. Mokler, Stein, and Armbruster[3]